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TRANSMITTERS, RECEIVERS, AND NOISE IN SOLITON COMMUNICATIONS

Final Report

9/20/93 – 9/19/97

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Abstract

Work on a four-year project to investigate soliton communications is summarized. Topics that we worked on included: (1) soliton switching, (2) polarization effects, (3) transmission impairments and signal processing, (4) soliton lasers, (5) non-Gaussian noise, (6) wavelength division multiplexing, and (7) dispersion-managed solitons. During this period, the outlook for soliton communications was poor for much of the time due to the great success of NRZ communication schemes; however, the recent advent of dispersion-managed solitons, to which we contributed both theoretically and experimentally, has turned the situation around. By contrast, the outlook for all-optical switching using solitons has become increasingly grim.

TRANSMITTERS, RECEIVERS, AND NOISE IN SOLITON COMMUNICATIONS

I. Summary of Progress

During this grant period extraordinary progress has been made on soliton communications—both internationally and in my group. Towards the middle of the contract period, the enormous strides that had been made in successfully using dispersion management to counteract the problems with standard NRZ (non-return-to-zero) communications had led virtually all system developers to abandon the notion that solitons could be successfully used in a communication system. This situation has been dramatically turned around within the past two years by the discovery that solitons can be combined with dispersion management to yield systems with many of the combined advantages of NRZ and more traditional soliton systems. My research group has participated in these developments both theoretically and experimentally. We have also contributed to the growing use of signal processing and to the development and use of new sources—including sources that now make the generation of solitons no more difficult than standard NRZ signals. Indeed, with the advent of phase and amplitude modulation in conjunction with NRZ systems, the acronym has become something of a misnomer, and these systems are increasingly referred to as “nearly return-to-zero.” Thus, the long NRZ vs. soliton debate may be on the verge of concluding with the two formats converging—an issue that we have also been exploring both theoretically and experimentally.

By contrast with soliton communications, the outlook for soliton switching has become increasingly grim over the contract period. Not only is all-optical switching hard to do and energetically costly, but the great success of electronic switches in achieving increasingly high data rates—along with their greater compactness and integrability—has made all-optical switching appear to be increasingly superfluous. We have played a role in theoretically elucidating all-optical switches in cooperation with two experimental groups: Mohammed Islam’s group which was at AT&T Bell Labs at the time of our cooperation and with Irl Duling’s group at the Naval Research Laboratory.

In the remainder of this report, I will describe our contributions by topic, correlating them with the publications that are listed in Sec. II.

A. Switching:

Our work on switching appeared in publications 5, 19, 26, and 30. The first two papers describe our work on the soliton dragging and trapping gates that were developed by Islam. Publication 5 discusses a reduced model approach based on the variational method that would allow us in principle to study the propagation of signals through a large number of gates. In fact, later work showed that the pulses distort so significantly even passing through just two gates that the use of this approach is invalid. Thus, this work can be viewed as an example of how *not* to use the variational approach. Publication 19 contains a thorough simulation of the four-gate code-matching logic module that Islam

and co-workers had proposed to use as a logic element in a ring network. We showed that while a parameter regime could be found in which it works, this parameter regime is small and unlikely to be found in practice. We note that shortly after the publication of this paper, Islam and his colleagues at the University of Michigan abandoned trapping and dragging gates in favor of loop mirrors.

Publications 26 and 30 concern work that we did to analyze loop mirrors that were then being studied experimentally by Irl Duling and his colleagues at the Naval Research Laboratory. They used standard communication fiber that had been unwound from its spool with a length of several hundred meters, amounting to several soliton periods for the sub-picosecond pulses that were being injected into the loop mirror. They found that polarization was well-preserved in the sense that orthogonal states remained orthogonal, although they changed along the fiber on a length scale of several meters. At the end of the fiber loop the state was then rectified using a polarization controller, and the effect of the nonlinear switching could thus be taken into account. This procedure worked very well—too well, in fact! The timing window was several times larger than it should have been. We analyzed this effect and showed that it was due to the randomly varying polarization walkoff that allowed the signal to slip through itself several times. In studying this system, we applied the ideas on nonlinear polarization mode dispersion that we had earlier developed in our study of polarization effects.

B. Polarization Effects:

Our work on polarization effects, which is contained in publications 1–3, 6, 8, 14, 16, 20, 32, 33, and 36, has a significance that goes far beyond solitons. The bulk of the work (all except 8 and 32) were aimed at taking advantage of the separation of length scales between the large but rapidly and randomly varying birefringence to derive equations that properly take into account the effects of chromatic dispersion, the Kerr effect, and polarization mode dispersion (PMD) on the long scale of optical transmission systems which is typically hundreds or even thousands of kilometers. A fundamental goal of this work was to explain a key theoretical mystery: Why does the nonlinear Schrödinger equation work? All derivations of this equation up to the time of our work were done supposing that the optical fiber is perfectly circular and that birefringence plays no role. In fact, just the opposite is true! We completely resolved this issue by showing that on the length scale of meters, on which the birefringence is fixed, the appropriate equation is the coupled nonlinear Schrödinger equation but on a longer length scale, when one averages over the rapidly varying birefringence, one obtains an equation that we call the Manakov-PMD equation. This equation contains the effects of chromatic dispersion and nonlinearity averaged over the Poincaré sphere with the by now well-known $8/9$ coefficient in front of the nonlinear term. This coefficient that we predicted, along with a group at AT&T Bell Laboratories, has now been confirmed by several experiments. It also contains all the linear PMD effects that had been studied by Poole and co-workers and by many others. Finally, it contains a new effect that we referred to as nonlinear PMD. While this last effect is interesting, we were able to show that it is negligibly small in communication fibers. It only becomes important in short pulse experiments like those of Irl Duling and his colleagues at the Naval Research Laboratory. In those experiments, we were able to see the effect

of nonlinear PMD. When linear PMD is also negligible, then the propagation is purely described by the Manakov equation. When the input signal is in a single polarization state as a function of time, then it will remain in a single polarization state as a function of time, although this state will rapidly change along the fiber. Under these circumstances, the nonlinear Schrödinger equation holds. This derivation is the only one that is valid for real communication fibers.

Additionally, however, this work led to a new algorithm for accurately determining the pulse evolution along the fiber, stepping on the length scale of the birefringence and the nonlinearity. We were also able to justify an *ad hoc* approach often found in the literature that we call the coarse step approach.

We have recently begun to push our work on polarization effects in two new directions. First, we have begun to look at the possibility of dynamically compensating for the polarization mode dispersion by changing the polarization states to match the so-called principal states. Second, we have begun a project in collaboration with the undersea light-systems group, formerly at AT&T and now at Tyco, investigating the effects that the polarization dependent loss, polarization dependent gain, and polarization mode dispersion have on fading in communication systems. Real systems use polarization scrambling to reduce these effects, but these systems often repolarize. We showed that the polarization dependent loss that is present in these systems can account for the repolarization in publication 32. This work is the first step in what is likely to be a long and interesting project.

C. Transmission Impairments and Signal Processing:

This work, which includes publications 4, 7, 11, 15, 21, 24, 37, and 38, all discuss the acoustic effect and its ramifications for communication systems, with the exception of publications 4, 11, and 38.

The acoustic effect, which is due to the electrostrictive force inside optical fibers, moves and decays at the speed of sound in the fiber and thus has a very long-term effect on soliton interactions. We found that polarizing adjacent bits orthogonally tends to reduce the acoustic effect. We also noted that the timing jitter induced by the acoustic effect is highly correlated—in contrast to the timing jitter that is induced by spontaneous emission noise, *e.g.*, the polarization effect or the Gordon-Haus effect. Consequently, simple forward error correction schemes, like a Hamming code, will fail to correct it. However, simple line coding which assures that there are an equal number of 0's and 1's within the correlation time of the acoustic effect will eliminate the problem with a relatively small overhead—an overhead that becomes smaller as the data rate increases. In collaboration with signal processing experts we are exploring more sophisticated approaches. We view this work as a first salvo in what we see as an effort to take greater advantage of signal processing techniques in optical fiber communications.

We have also begun an effort to look at phase and amplitude modulation in conjunction with non-return-to-zero systems. Publication 38 summarizes our work to date on this issue.

In other work, we have investigated the implications of the Brillouin effect for soliton propagation and explored the relative merits of up-sliding vs. down-sliding in sliding filters.

D. Lasers:

The study of laser sources has not been a big thrust for us theoretically. However, important progress was made during the contract period by the development at what was then AT&T Bell Laboratories by P. Mamyshev of a simple soliton source. This source consists of a laser diode followed by a LiNbO_3 amplitude modulator, just as in an NRZ source, followed by a LiNbO_3 phase modulator. This device later served as the source for our own experimental efforts on dispersion-managed solitons which I will describe later. We collaborated with P. Mamyshev in a theoretical study of this soliton source, and this work is described in publication 13.

Other work that we carried out on lasers included a study of the conditions for a passively modelocked laser to self-start which is found in publication 10, and the impact of the acoustic effect on ring lasers which is found in publication 12.

E. Non-Gaussian Noise:

Since the optical fiber is a nonlinear transmission channel, there is no reason *a priori* why spontaneous emission noise (which is a Gaussian noise source) should lead to a Gaussian distribution of the physical quantities of interest such as the timing jitter of a soliton. Actually, a single soliton is a pure nonlinear mode of the channel and, hence, its timing jitter is Gaussian, but the separate solitons interacting in a communication channel are no longer pure modes. To understand the impact that nonlinearity can have on the tails of a distribution function, we investigated the distribution function for timing jitter in the presence of a mutual interaction, and we showed that it can lead to a significant stretching of the tail with very little change in the standard deviation of the timing jitter. This effect would be completely impossible to observe using standard Monte Carlo simulations and required the development of new mathematical tools. These tools, which are known as large deviation techniques in the mathematics and communication engineering communities, allow us to in effect turn a microscope onto the portion of the distribution function that is most likely to lead to errors. This work was presented in publications 9 and 21.

Due to work by T. Georges, it has become apparent that the largest source of non-Gaussian tails in practical systems is likely to be the nonlinear nature of the filters in real systems. A graduate student has been working on this issue, but his progress has been slow. It is my belief that in the long run this issue and its resolution will be highly important. For systems other than soliton systems, or even dispersion-managed soliton systems, it is a sufficient challenge just to find the linear noise response that we have put this problem aside for now.

F. Wavelength Division Multiplexed Systems:

It has been apparent for some time that if soliton systems were going to be successful, then they would be developed in conjunction with wavelength division multiplexing (WDM) in which a number of different wavelength channels would be transmitted at once to achieve a high throughput. Our work on wavelength division multiplexing is contained in publications 17, 18, 28, and 31. Publications 17 and 18 contain our work considering the limits on channel spacing for standard solitons that exist in both filtered and unfiltered

systems. In our work on unfiltered systems we determined the tolerance limits that exist on gain differences due to lack of flatness in the erbium-doped fiber amplifiers at different wavelengths. We also determined the limitations imposed by solitons in different channels that overlap at the receiver end. This effect is unavoidable in real systems. The minimum frequency spacing allowed by this effect is roughly four times the spectral full width at half maximum. We next considered the penalty that is paid in filtered systems by using Fabry-Perot filters. Here we find that a limitation is also imposed by the requirement that the minimum in the transmission curve should be deep enough to stabilize the solitons without inducing too much excess loss. We found that the channel spacing in this case should be five times the spectral full width at half maximum so that there is very little penalty incurred by using filters.

Publications 28 and 31 contain our work on wavelength division multiplexing in conjunction with dispersion-managed solitons, and we will discuss this work in that context. Suffice it to say here that WDM performs quite well in that context.

G. Dispersion-Managed Solitons:

As mentioned in the introduction, the advent of dispersion-managed solitons has completely revolutionized the way in which solitons are viewed. It is quite clear at this point that if solitons are to be used in practice they will be dispersion-managed. Our group has played a key role in the development of this concept. We started work on this subject because we wished to construct a testbed that would allow us to transmit both NRZ and soliton signals with a view toward determining the physical impairments that actually limit the achievable bit rates. Such a system has to be dispersion-managed, and our original design showed clearly the enhancement factor which is one of the principal advantages of the dispersion-managed soliton: For a given average dispersion, the dispersion-managed soliton has more average energy than a standard soliton. Thus, its Gordon-Haus jitter will be reduced. At about the time that we completed our loop and began carrying out experiments, the group of N. Doran showed theoretically that experiments carried out by the group of M. Suzuki in Japan with dispersion-management had similar enhancement factors. We then began our own detailed theoretical studies of dispersion-managed systems. Currently, there is a large number of theoretical groups investigating these issues; however, our group remains unique in the close tie that we have been able to establish between theory and experiment. Our work on these solitons is contained in publications 23, 25, 27-29, 31, 34, 35, 39, and 40.

Dispersion-managed solitons are periodically stationary pulses that propagate in a dispersion map that has alternating spans of positive and negative dispersion. The dispersion in the individual spans is sufficiently large that the pulses undergo large changes, stretching and compressing, while propagating in the dispersion map. Thus, the "solitons" in this system are in no sense standard solitons. Unlike standard solitons, they are not absolutely stationary; instead, they are only periodically stationary, returning to the same shape after propagating through one period of the dispersion map. Moreover, their shape differs radically from a standard soliton which is a hyperbolic secant pulse. Instead, dispersion-managed solitons change from a hyperbolic secant shape to a Gaussian shape to a shape that is flat-topped with weak oscillating wings as the strength of the dispersion

management is increased. However, their behavior is in all respects superior to standard solitons.

First, they are less susceptible to Gordon-Haus jitter. As previously mentioned, their amplitude for a given average dispersion can be considerably higher than for standard solitons, leading to a reduction in the Gordon-Haus jitter by the enhancement factor—the ratio of the soliton amplitudes. This factor was used in publication 27 to explain the experimental data, and we found excellent agreement. More recently, we have carried out detailed simulations, and we have shown that there is a discrepancy from the factor predicted by the enhancement factor. We have explained this discrepancy by taking into account the changing shapes, and this result is being prepared for publication.

Second, they are less susceptible to mutual interactions. Because neighboring solitons tend to interact nonlinearly, they must be spaced apart a minimum distance to avoid their mutual attraction. We showed in publication 29 that this minimum distance grows rapidly with the enhancement factor up to a maximum that is set by the pulse shape. The mutual interaction is minimized when the pulse shape is closest to Gaussian. Thus, the signals can be spaced somewhat closer together.

Third, WDM works as well with dispersion-managed solitons as it does with solitons in ideal, exponentially-tapered fibers. This result, which is contained in publications 28 and 31 is highly significant because exponentially-taped fibers are nearly impossible to construct, and one must use multi-step approximations that perform considerably worse. By contrast, it is easy to construct dispersion maps, and, indeed, that is how all current communication systems based on NRZ are being built!

In addition to the experimental work presented in publications 23, 27, 34, and 39 and our loop design simulations, presented in publication 25, we have carried out other theoretical investigations, such as the development of a variational approach detailed in publication 35.

Recently, we and other groups have found that it is possible to propagate solitons in the normal dispersion regime of optical fibers! The implications of this result are not currently known, but clearly there is much exciting progress that has yet to be made.

II. Publications and Conference Presentations

Publications:

1. C.R. Menyuk and P.K.A. Wai, "Polarization Evolution and Dispersion in Fibers With Spatially Varying Birefringence," J. Opt. Soc. Am. B **11**, 1288–1296 (1994).
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9. C.R. Menyuk, "Non-Gaussian Corrections to the Gordon-Haus Distribution Resulting From Soliton Interactions," *Optics Lett.* **20**, 285-287 (1995).
10. C.-J. Chen, P.K.A. Wai, and C.R. Menyuk, "Self-starting of Passively Mode-locked Lasers With Fast Saturable Absorbers," *Optics Lett.* **20**, 350-352 (1995).
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40. E.A. Golovchenko, A.N. Pilipetskii, and C.R. Menyuk, "Collision-Induced Timing Jitter Reduction by Periodic Dispersion Management Soliton WDM Transmission," in *System Technologies*, edited by A.E. Wilner and C.R. Menyuk, Trends in Optics and Photonics, vol. 12 (Optical Society of America, Washington, DC, 1997), pp. 288-291.

*Conference Presentations: (* marks invited presentation)*

- *1. C.R. Menyuk, C.-J. Chen, and P.K.A. Wai, "Passive Modelocking in Fiber Lasers," Nonlinear Guided Wave Phenomena Topical Meeting, Cambridge, England (Sept. 20-22, 1993), paper WA1-1.
- 2. P.K.A. Wai, C.R. Menyuk, and H.H. Chen, "Polarization Dispersion in Optical Fibers With Randomly Varying Birefringence," Optical Society of America Annual Meeting, Toronto, Canada (Oct. 3-8, 1993), paper TUS8.
- 3. C.-J. Chen, P.K.A. Wai, and C.R. Menyuk, "Stability of passively-mode-locked lasers with fast saturable absorbers," 9th Interdisciplinary Laser Science Conference, Toronto, Canada (Oct. 3-8, 1993), paper WT6.
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